PATENT SPECIFICATION

DRAWINGS ATTACHED

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COMPLETE SPECIFICATION

Gas-Lubricated Bearing

We, NATIONAL RESEARCH DEVELOPMENT CORPORATION, of 1, Tilney Street, London, W.1, a British Corporation established by statute, do hereby declare the invention, for which we pray that a patent may be granted to us and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to bearings where the bearing members are capable of relative movement in a plane and where gas under pressure is introduced between the relatively movable members place of conventional lubricants.

According to the invention there is provided a gas lubricated bearing having two co-operating members, a first member and a second member, a clearance space between the two members, which are capable of relative movement in a plane, a passage for the supply of gas under pressure to the clearance space to maintain such clearance space, at least one chamber in the first member, a restricted passage in the first member communicating with the chamber and adapted to offer resistance to the flow of gas, the chamber communicating with the clearance space to form a pressure zone, the zone being bounded in part by a surface of the second member, the chamber being so shaped, its associated restricted passage being so proportioned and located relative to the chamber and its associated pressure zone being so located relative to the chamber and to the second member that any oscillation of the members relative to each other, in a direction such as to increase or decrease the clearance space, sets up correspondingly periodic gas pressure alternations in the pressure zone having a phase such that pressure maxima occur when the relatively oscillating members are in an intermediate position of relative oscillatory displacement and are moving towards one another so as to decrease the clearance space.

According to the invention there is further provided a bearing comprising two members, each member having a surface which co-operates with a similar surface on the other member with a clearance space between them, either or both members being capable of movement in a plane, at least one inlet passage communicating with the clearance space for the introduction of gas under pressure into the clearance space to maintain such clearance space, at least one escape passage communicating with the clearance space for the escape of said gas under pressure, at least one opening in one of the members communicating with the clearance space (which opening may perform the function of either the said inlet passage or said escape passage) the said opening being so located, in relation to said inlet and escape passages, as to produce a flow of gas between the opening and the clearance space which flow is varied by reason of, and is related in the phase of its variations to any oscillations of one of the members relative to the other member in a direction having vector component perpendicular to the said plane and pneumatic phase shifting means associated with the opening arranged to derive from such variations of gas flow a correspondingly varying gas pressure in the said opening, the phase of which is such that the resulting force, acting on the surface of the member opposite the said opening, has a vector component the maxima of which coincide with velocity maxima of oscillation of the member or members, perpendicular to each other, and the sign of which vector component is such as to oppose the said oscillation.

The invention will be more clearly understood from the following detailed description of certain embodiments of the invention illustrated in the drawings accompanying the Provisional Specification in which:—

Fig. 1 is a diagrammatic representation of a gas-lubricated bearing of a known type.

Fig. 2 is a graph relating to the operation of the bearing in Fig. 1.

Fig. 3 is a diagrammatic representation of

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Price 2s

another known type of gas-lubricated bearing.

Fig. 4 is a graph relating to the operation of the bearing in Fig. 3.

Fig. 5 is a diagrammatic representation of a bearing according to the invention.

Fig. 6 is a vector diagram relating to the operation of the bearing in Fig. 5.

Fig. 7 is a diagrammatic representation of another bearing according to the invention.

Fig. 8 is a diagrammatic representation of a third bearing according to the invention.

Fig. 9 is a vector diagram relating to the operation of the bearing in Fig. 8.

Fig. 10 is a cross section of part of a fourth bearing according to the invention.

Fig. 11 is a vector diagram relating to the operation of the bearing in Fig. 10.

In bearings of the air lubricated type hitherto known, an example of which is illustrated in Fig. 1, a body 1 having a plane lower surface of extended area is separated from a pad 2 by means of a thin film of gas disposed in a clearance space 3, the gas being supplied under pressure to an injector hole 4 in the pad 2.

The gas film from the injector hole supports the plane surface with a force which increases when the clearance 3 is decreased, the relationship between the supporting force F and depth h of clearance 3 being shown in Fig. 2, from which it will be seen that the restoring force F becomes negative when the clearance exceeds a certain depth. This is a well known effect.

In an alternative type of bearing as shown in Fig. 3, the gas is supplied through a small orifice 4, to a shallow depression. In this case F varies with h as shown in Fig. 4.

A bearing of either of the types shown in Figs. 1 and 3 provides a restoring force which is approximately proportional to the displacement and consequently it behaves like a spring. The mass supported by the pad 2 is thus effectively supported on a spring, and an externally applied shock or impulse will set the system into oscillation, the frequency of the oscillation being given by:—

$$2\pi f = \sqrt{\frac{y}{m}}$$

where y is the stiffness of the spring and m is the apparent mass of the body 1 in a direction normal to the plane of the pad 2.

The amplitude of such oscillation decreases slowly with time, i.e. the system is lightly damped.

In the arrangement shown in Fig. 1 oscillation of the said plane surface 1 modulates a gas stream which is supplied through the jet 4 so as to provide an alternating component of current in the supplied gas. When the oscillation modulates the gas supply in this manner the modulated pressure peaks of the resulting alternating pressure component coincide in time with the instants of maximum displacement of the said plane surface from its equilibrium position. At these instants the oscillation velocity of the plane is at a minimum since the velocity and displacement are in quadrature with one another. For the maximum resistance to oscillation the pressure peaks should coincide with instants of maximum velocity of the plane and it is therefore necessary for the alternating pressure components produced by modulation of the gas supply on oscillation of the plane to differ in phase, ideally by 90°, irrespective of oscillation frequency. This ideal phase angle may not be achieved at all frequencies in practical arrangements according to the invention but an approximation to the ideal phase shift gives a marked superiority over previously known gas lubricated bearings.

For the purpose of analysing and defining the phase relationships of the various gas streams and oscillations, the oscillation of the said plane surface may be regarded as the projection on a line normal to the plane of a complex vector ϵ which rotates with an angular velocity $\omega = 2\pi f$, where f is the frequency of oscillation. The distance h between the plane and the pad at a given time t is given by

$$h = \delta - \epsilon \cos \omega t$$

where δ is the mean separation.

The various gas streams, pressures and forces can likewise be represented by complex vectors which have definite phase relationships with the complex vector of oscillation.

A number of arrangements according to the invention, for inhibiting oscillation, will now be described in relation to the Figs. 5 and 11.

In the embodiment shown in Figure 5 a body 1 having a plane lower surface is supported a short distance away from a disc or pad 2 by means of a film of gas which is supplied under pressure to an injector hole 4 in the centre of the pad. The gas from the clearance flows into an annular cavity 3 of capacity C, formed in the upper surface of the pad and surrounding the hole 4. From the cavity 3 most of the gas escapes through an orifice 20 of resistance R. The remainder escapes through the clearance between the said plane surface and the outer periphery of the annular cavity. Assuming for simplicity of analysis that the latter escape of gas is negligibly small (although in practice it may be appreciable) the plane surface forms a part of the walls of the cavity, 3, so that the gas pressure in the cavity exerts a force on the plane equal to the product of that pressure and the area of the plane which forms part of the cavity wall.

The current of gas entering the cavity 3 of Figure 5 will consist of a steady component and an alternating component whose peak value is proportional to the peak amplitude of

oscillation of the said plane surface from its equilibrium position. The capacity C and the resistance R which are, (to use an electrical analogy), effectively in parallel, present an impedance Z to the alternating component I of the current, and thus the alternating pressure $p\omega$ in the cavity is given by the equation $p\omega = IZ$

$$\text{where } Z = \frac{1}{\sqrt{\frac{1}{R^2} + (2\pi f C)^2}}$$

f being the frequency of oscillation. The pressure $p\omega$ lags behind the current I, the phase angle being given by

$\tan\alpha = R\omega C$, or $\sin\alpha = Z\omega C$

where $\omega = 2\pi f$.

This is represented vectorially in Figure 6 the left hand portion of which shows the phases of the gas currents. The vertical vector I_R represents the current flowing in the resistance R, the horizontal vector I_C represents the current flowing in the cavity 3 and the slanting vector $I\epsilon$ represents the resultant of the other two currents and is in phase with the oscillatory displacement vector ϵ of the said plane surface.

The right hand portion of Figure 6 shows the corresponding pressure phase relationship to the dotted vector ϵ representing the oscillatory displacement of the said plane surface from its equilibrium position. Vector $p\omega$ is in phase with I_R and represents the alternating pressure in cavity 3 and it is shown resolved into a component $p\omega \cos\alpha$ in phase with the displacement vector and a component $p\omega \sin\alpha$ in quadrature with the displacement vector. This quadrature pressure component acting on the area A of the said plane surface, opposite the cavity, resists motion due to oscillations of the plane.

In an alternative embodiment the stabilising cavity is separated from the supporting disc. The plane surface is supported, a short distance from the stabilising system. Figure 7 shows such a system and gas flows into the cavity 3 through the clearance between the said plane surface and the annular surrounding margin of the cavity. This requires the pressure surrounding the cavity to be greater than the pressure at the outlet of the resistance orifice R. Any oscillation of plane modulates the gas stream flowing into the cavity and the stabilising action is exactly the same as in the arrangement of Figure 5.

A further embodiment of the invention is shown in Figure 8. Here the clearance h, between the pad and the said plane surface of body 1 is enlarged as compared with the previously described embodiments. The effect of this is that the said plane surface is attracted towards the pad when gas under pressure is forced through the entry hole 4 into the clearance space.

This is a well known phenomenon and the explanation of it is apparent on inspection of Figure 2 where it is seen that, with clearances above a certain size (.002 in the instance to which Figure 2 relates), the force F becomes negative.

The attractive force is approximately proportional to the pressure in the gas entry hole 4.

Gas is supplied to the clearance space through a narrow inlet 20 having a resistance R into a cavity 3 of capacity C and thence through hole 4 into the clearnce space between the pad and the said plane surface.

The various phase relationships are illustrated vectorially in Figure 9. If the said plane surface oscillates at a frequency f and with an amplitude ϵ the pressure in the cavity 3 will have an alternating component $p\omega$.

If the flow of gas entering the cavity 3 through resistive passage 20 is constant and supposing that the pressure ratio across the resistive passage 20 is greater than 2, the alternating component of the current I_B, in the entry hole 4 is given by the equation $I_B = p_\omega \omega C$ (where $\omega = 2\pi f$) and is in quadrature with the pressure p_ω. The effective size of entry hole 4 varies inversely with the clearance h and it has a resistance R_o (its resistance with the body 1 stationary and the clearance at its normal or mean value) and when the said plane surface of 1 is oscillating, a varying component of resistance $R\omega$ is added.

The left hand diagram of Figure 9 shows a current vector

$$I_{R_o} = \frac{p\omega}{R_o}$$

leading the current I_B by 90° and the resultant of these two currents (I_B and I_{Ro}) is $I\epsilon$ and is in antiphase with the displacement vector ϵ, shown dotted on the right hand diagram of the Figure.

The alternating pressure component $p\omega$ is in phase with I_{Ro} and it can be resolved into a component $p\omega \cos\alpha$ in phase with the displacement vector ϵ, and a component $p\omega \sin\alpha$ in quadrature with the displacement vector ϵ so that when h is increasing $p\omega$ is large, thus resisting the increase of h.

A further embodiment of the invention is illustrated in Figure 10.

A shallow cavity 3 is formed in the surface of the pad facing the said plane surface of the object 1. Gas supply to the cavity 3 is controlled by a pneumatic amplifier which responds to pressure variations in cavity 3 with a lagging phase relationship.

The response is such that an increase of pressure in cavity 3 results in a decrease of current.

Gas enters a cavity 11 from which a passage 4 leads to cavity 3. A diaphragm 5, which forms one wall of cavity 11, co-operates with a raised seating 6 formed at the end of passage 4 remote from cavity 3, to control the flow of gas into cavity 3. Diaphragm 5 is urged towards seating 6 by a spring 7 which may be adjusted by means of a screwed plug 7a. The other side of diaphragm 5 forms a wall of a closed cavity 9 the only access to which is through a hole 10 in diaphragm 5.

Gas at constant pressure is supplied to cavity 11 and lifts diaphragm 5 off the valve seating 6 against the force of spring 7 thus admitting gas to cavity 3. Gas entering cavity 3 escapes through the clearance between the surface of the wall surrounding cavity 3 and the said plane surface of 1. Gas from cavity 3 also leaks into cavity 9 through a reistance constituted by the hole 10 in diaphragm 5, though an alternative passage could be provided. The pressure in cavity 9 builds up with a time constant $t=R_{10}C_9$ where R_{10} is the resistance of hole 10 and C_9 is the capacity of cavity 9. Equilibrium is reached when the pressure in cavity 9 becomes equal to the pressure in cavity 3. The volume of cavity 3 is made as small as possible.

In the steady state let p_o be the pressure in cavity 3 and R_o the resitance of the leak past the edges of the cavity 3.

If the said plane surface oscillates at a frequency f the pressure in cavity 3 becomes $p_o+p\omega$ and the resistance of the leak becomes $R_o+R\omega$.

The current leaking past the edges of cavity 3 is given by the expression

$$\frac{\underline{p}_o+\underline{p}_\omega}{\underline{R}_o+\underline{R}_\omega}$$

For small amplitudes of oscillation this expression may be expanded to:

$$\frac{\underline{p}_o+\underline{p}_\omega}{\underline{R}_o\ \underline{R}_o} - \frac{\underline{p}_o\cdot\underline{R}_\omega}{\underline{R}_o^2} - \frac{\underline{p}_\omega\cdot\underline{R}_\omega}{\underline{R}_o^2}$$

The last term is small and may be neglected. The first term represents the steady component of flow through cavity 3.

In cavity 9 the phase of the pressure lags behind the phase of the pressure in cavity 3. The alternating component I_3 of the current entering cavity 3 is in antiphase with this pressure.

Vector diagrams for the pressure and currents are shown in Figure 11.

The second term of the above expanded expression for the current may be called I_{Ro} and is represented by the vertical vector of the left hand part of Figure 11. Joined to the top of this is the vector I_{10} representing the current through hole 10. Joined to the bottom of the I_{Ro} vector is the vector I_6 representing the current passing through the varying space between the diaphragm 5 and the seating 6. $I_6 = g\,\frac{(I_{10})}{(C_9)}$ and the term in brackets represents the movement of diaphragm 5 whilst the symbol g represents the amplification factor (or gain) of the pneumatic amplifier constituted by the valving action of diaphragm 5 in co-operation with seating 6. Joined to the left hand end of vector I_6 is vector I_3 which is equal to $p_\omega\,\omega C_3$ and represents the current flowing in cavity 3. Joining the ends of vectors I_3 and I_{10} is the vector $I\epsilon$ which represents the third term of the above expanded expression for current namely,

$$\frac{\underline{p}_o\cdot\underline{R}_\omega}{\underline{R}_o^2}$$

which is in phase with the oscillatory displacement of the said plane surface.

The right hand side of Figure 11 shows the pressure vectors. A vertical vector p_ω is parallel to the I_{Ro} current vector and the displacement vector ϵ, which is shown by a dotted line, is parallel to the $I\epsilon$ vector on the left. The pressure vector $p\omega$ may be resolved into two vectors, $p\omega \cos\alpha$ in antiphase with the displacement vector ϵ and $p_\omega \sin\alpha$ in quadrature with the displacement vector ϵ which latter component, acting on the said plane surface, resists oscillation thereof, and by a suitable choice of values, stability may be ensured.

The said plane surface, in the absence of any oscillatory tendency, will take up a position in relation to the pad which depends principally on the amount of gas entering cavity 3, which may be regulated by adjustment of spring 7 by means of plug 7a.

Taking the example illustrated in Figure 5, for a load of 14 kilogrammes, and a supply pressure of 7 atmospheres absolute, the dimensions are as follows:—The pad 2 consists of a cylindrical member 8 centimeters in diameter, and of a depth suitable for the installation concerned, for example 3 centimetres. The injector hole 4 is situated at the centre of the pad and has a diameter of .4 centimetres. The cavity 3 is annular in formation, the inside diameter of the annulus being 6 centimetres and the external diameter being 7 centimetres. The cavity, therefore, has a rectangular cross-section which is .5 centimetres wide and its depth is 1.39 centimetres. It is substantially symmetrical about the injector hole 4. A single orifice 20 is positioned at any suitable

position in the bottom of the cavity and has a diameter of .255 centimetres. The clearance H at the stated load is .002 inches, which is approximately .005 centimetres.

For the eaxmple illustrated in Figure 8, for a load of 5.25 kilogrammes and a supply pressure of 14 atmospheres absolute, the dimensions are as follows:—The pad 2 is cylindrical, having a diameter of 6 centimetres. The depth of the pad will depend on that required to contain the various items, i.e. the injector 4, cavity 3, orifice 20, and means for connecting the supply plug. In the example considered, it is approximately 2 centimetres. The injector hole 4 is .4 centimetres diameter, and is situated centrally in the pad 2. The orifice 20, through which is supplied the air, is .078 centimetres in diameter. For the operating conditions given, the volume of the cavity 3 is .0315 cubic centimetres. Conveniently, the diameter of the cavity can be made .525 centimetres, the depth of the cavity being .146 centimetres.

In a practical application, for instance to a sliding carriage required to move in one direction along a slideway, five supporting pads could be used, mounted on two inclined planes on a slideway, and co-operating with two correspondingly inclined flat planes on the carriage. Two longitudinally displaced pads would co-operate with each inclined plane and a fifth pad would be required on one of the planes, vertically displaced from the other two pads in that plane, to prevent rotation of the carriage around the axis of intended movement. Not all these pads need necessarily incorporate oscillation stabilising cavity systems and those not so equipped could take the form of Figure 1 or 3. In such a case the oscillation stabilising cavity systems would be confined to to the positions required to suppress oscillation in directions where oscillation might be expected to occur.

In such an arrangement the five pads would act in opposition to the weight of the carriage, which would generally be sufficient to avoid lifting of the carriage but downwardly facing pads could also be furnished if required.

In a further practical application, for instance a thrust bearing, the thrust load could be taken on one or more supporting pads. Any rocking movement of the axis of the shaft could be contained either by journal bearings of known type, or by the stabilised gas lubricated type according to my co-pending Patent Application No. 7714/55 (Serial No. 797,528).

In the above descriptions, the supporting pads have been shown as co-operating with a plane surface on the object supported. This surface need not necessarily be flat, the surfaces of the two members being shaped to cooperate.

WHAT WE CLAIM IS:—

1. A gas lubricated bearing having two cooperating members, a first member and a second member, a clearance space between the two members, which are capable of relative movement in a plane, a passage for the supply of gas under pressure to the clearance space to maintain such clearance space, at least one chamber in the first member, a restricted passage in the first member communicating with the chamber and adapted to offer resistance to the flow of gas, the chamber communicating with the clearance space to form a pressure zone, the zone being bounded in part by a surface of the second member, the chamber being so shaped, its associated restricted passage being so proportioned and located relative to the chamber and its associated pressure zone being so located relative to the chamber and to the second member that any periodic oscillation of the members relative to each other, in a direction such as to increase or decrease the clearance space, sets up correspondingly periodic gas pressure alternations in the pressure zone having a phase such that pressure maxima occur when the relatively oscillating members are in an intermediate position of relative oscillatory displacement and are moving towards one another so as to decrease the clearance space.

2. A bearing comprising two members, each member having a surface which co-operates with a similar surface on the other member with a clearance space between them, either or both members being capable of movement in a plane, at least one inlet passage communicating with the clearance space for the introduction of gas under pressure into the clearance space to maintain such clearance space, at least one escape passage communicating with the clearance space for the escape of said gas under pressure, at least one opening in one of the members communicating with the clearance space (which opening may perform the function of either the said inlet passage or said escape passage) the said opening being so located, in relation to said inlet and escape passages, as to produce a flow of gas between the opening and the clearance space which flow is varied by reason of, and is related in the phase of its variations to, any oscillation of one of the members relative to the other member in a direction having a vector component perpendicular to the said plane and pneumatic phase shifting means associated with the said opening arranged to derive from such variations of gas flow a correspondingly varying gas pressure in the said opening, the phase of which is such that the resulting force, acting on the surface of the member opposite the said opening, has a vector component the maxima of which coincide with velocity maxima of oscillation of the member or members perpendicular to each other, and the sign of which vector component is such as to oppose the said oscillation.

3. A bearing as claimed in claim 2 with one or more inlet passages in the member con-

taining the said opening, which passage or passages communicate with the clearance space and are additional to and associated with said opening, from which gas under pressure may be caused to flow into such opening via the clearance space so that the rate of such flow is varied by and in phase with the said perpendicular vector component of any relative oscillation between the two members, the said pneumatic phase shifting means comprising a cavity associated with each opening which may be the opening itself, associated with each cavity a passage restricted so as to offer resistance to the flow of gas to or from the cavity, the cavity and restricted passage being so proportioned that on relative oscillation of the members in a direction having a perpendicular vector component as aforesaid, a varying gas pressure is applied to the surface of the member opposite the said opening which varying gas pressure is shifted in phase in relation to the variations of gas flow into that opening from the clearance space.

4. A bearing as claimed in claim 2 in which each said passage for the introduction of gas under pressure into the clearance space has a duct section of restricted cross section so as to offer resistance to flow of gas therethrough, a cavity and a section forming one of the said openings, and in which there is provided at least one passage for the escape of gas from the clearance space, the duct section and cavity constituting at least part of the said pneumatic phase shift means.

5. A bearing as claimed in claim 2 having a movable control member controlling the flow of gas between the openings and the clearance space and, associated with each of the said openings, a cavity (which may be common to two or more openings) and a duct of restricted cross section so as to offer resistance to the flow of gas into or out of the cavity, the said movable control member being responsive to varying pressures in the cavity to vary the flow of gas through the said opening (or openings) so as to amplify pressure variations therein, the cavity and duct constituting at least part of the said pneumatic phase shift means.

6. A bearing as claimed in claim 5 in which the movable control member is a diaphragm forming at least part of one wall of the cavity referred to in claim 5.

7. A bearing as claimed in claim 6 in which the duct of restricted cross-section referred to in claim 5 consists of a hole in said diaphragm.

8. A bearing substantially as described and as shown in Figs. 5 and 6 of the accompanying drawings.

9. A bearing substantially as described and as shown in Fig. 7 of the accompanying drawings.

10. A bearing substantially as described and as shown in Figs. 8 and 9 of the accompanying drawings.

11. A bearing substantially as described and as shown in Figs. 10 and 11 of the accompanying drawings.

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PROVISIONAL SPECIFICATION

Gas-Lubricated Bearing

We, NATIONAL RESEARCH DEVELOPMENT CORPORATION, of 1 Tilney Street, London, W.1, a British Corporation established by Statute, do hereby declare this invention to be described in the following statement:—

This invention relates to bearings which are lubricated by gas.

There are certain applications in engineering where the use of liquid lubricated bearings is inconvenient or impracticable. In such cases it is known that the relatively moving surfaces may be separated by means of a thin film of compressed gas. Such bearings are known as "externally pressurised gas lubricated bearings" or "aerostatic bearings".

In the copending patent application No. 7714/55 (Serial No. 797528), there is described a rotating bearing of this type with certain novel features.

It is now proposed to provide a similar bearing for supporting two relatively movable bodies for relative movement in a plane.

The invention will be more clearly understood from the following description of certain embodiments illustrated in the accompanying drawings.

A component of a bearing of the type described is shown in Figure 1. It comprises a body 1 having a plane lower surface of extended area which is separated from a pad 2 by means of a thin film of gas disposed in a clearance space 3 the gas being supplied under pressure to an injector hole 4 at the centre of the pad 2.

The gas film from the injector hole supports the plane surface with a force which increases when the escape path via the clearance 3 is reduced, the relationship between the supporting force F and the said clearance escape path of depth h, being shown by the curve of Figure 2 from which it will be seen that the force F becomes negative when the clearance exceeds a certain size. This is a well known effect.

An alternative type of bearing component is shown in Figure 3. The pad is provided with a shallow depression which is supplied with compressed gas through a small orifice or

resistance. In this case F varies with h approximately as shown in Figure 4.

A bearing component or unit of either of these types can only be relied upon to provide a single constraint normal to its surface, and consequently a complete bearing with the usual single degree of freedom requires a minimum of five pads providing five constraints, thus leaving one degree of freedom.

A bearing unit of either of the types shown in Figures 1 and 3 provides a restoring force which is approximately proportional to the displacement and consequently it behaves like a spring. The mass supported by the pad is thus effectively supported on a spring, and in the event of an externally applied shock or impulse will set the system into oscillation; the frequency f of oscillation being given by

$$2\pi f = \sqrt{\frac{y}{m}}$$

where y is the stiffness of the spring and m is the apparent mass of the body 1 in a direction normal to the plane of the pad.

The amplitude of such oscillation decreases slowly with time, i.e. the system is lightly damped.

To obviate this it is necessary to provide a force which resists the oscillation of the body with respect to the pad and causes the amplitude of any accidentally excited oscillation to decrease rapidly with time. For this purpose a gas, preferably air, is supplied under pressure from an external source, and oscillation of the plane surface of body 1 modulates the gas stream which flows through the clearance between the pad and the said plane surface so as to provide an alternating component of current in the gas stream, a pneumatic network being provided which either alone or in conjunction with a pneumatic amplifier generates a component of pressure whose phase differs from that of the current. This pressure component is applied to an area of the said plane surface so that it generates an alternating force of a phase such that it resists oscillation of the plane.

For the purpose of analysing and defining the phase relationships of the various gas streams and oscillations the oscillation of the said plane surface may be regarded as the projection on a line normal to the plane of a complex vector ϵ which rotates with an angular velocity $\omega = 2\pi f$, where f is the frequency of oscillation. The distance h between the plane and the pad at a given time t is given by

$$h = \delta - \epsilon \cos \omega t$$

where δ is the mean separation.

The various gas streams, pressures and forces can be likewise represented by complex vectors which have definite phase relationships with the complex vector of oscillation.

In the arrangement of Figure 1 oscillation of the said plane surface modulates a gas stream which is supplied through the hole 4 in the centre of the pad so as to provide an alternating component of current in the supplied gas. When the oscillation modulates the gas supply in this manner the modulated pressure peaks coincide in time with the instants of maximum displacement of the said plane surface from its equilibrium position. At these instants the oscillation velocity of the plane is at a minimum since tht velocity and displacement are in quadrature with one another. For the maximum resistance to oscillation the pressure peaks should coincide with instants of maximum velocity of the plane, and it is therefore necessary for the alternating pressure components produced by modulation of the gas supply by oscillations of the plane, to differ in phase, ideally by 90°, irrespective of oscillation frequency. This ideal phase angle may not be achieved at all frequencies in practical arrangements according to the invention but an approximation to the ideal phase shift gives a marked superiority over previously known gas lubricated bearings.

A number of oscillation inhibiting arrangements will now be described in relation to Figures 5 to 11 of the accompanying drawings.

In the embodiment shown in Figure 5 a body 1 having a plane lower surface is supported a short distance away from a disc or pad 2 by means of a film of gas which is supplied under pressure to an injector hole 4 in the centre of the pad. The gas from the clearance flows into an annular cavity 3 of capacity C, formed in the upper surface of the pad and surrounding the hole 4. From the cavity 3 most of the gas escapes through an orifice 20 of resistance R. The remainder escapes through the clearance between the said plane surface and the outer periphery of the annular cavity. Assuming for simplicity of analysis that the latter escape of gas is negligibly small (although in practice it may be appreciable) the plane surface forms a part of the walls of the cavity 3, so that the gas pressure in the cavity exerts a force on the plane equal to the product of that pressure and the area of the plane which forms part of the cavity wall.

The current of gas entering the cavity 3 of Figure 5 will consist of a steady component and an alternating component whose peak value is proportional to the peak amplitude of oscillation of the said plane surface from its equilibrium position. The capacity C and the resistance R which are, (to use an electrical analogy), effectively in parallel, present an impedance Z to the alternating component I of the current, and thus the alternating pressure p_ω in the cavity is given by the equation $p_\omega = IZ$

$$\text{where } \underline{Z} = \sqrt{\frac{1}{\frac{1}{\underline{R}^2} + (2\pi f \underline{C})^2}}$$

f being the frequency of oscillation. The pressure p_ω lags behind the current I, the phase angle being given by

$\tan \alpha = R\omega C$, or $\sin \alpha = Z\omega C$

where $\omega = 2\pi f$

This is represented vectorially in Figure 6 the left hand portion of which shows the phases of the gas currents. The vertical vector I_R represents the current flowing in the resistance R, the horizontal vector I_C represents the current flowing in the cavity 3 and the slanting vector I_ϵ represents the resultant of the other two currents and is in phase with the oscillatory displacement vector ϵ of the said plane surface.

The right hand portion of Figurt 6 shows the corresponding pressure phase relationship to the dotted vector ϵ representing the oscillatory displacement of the said plane surface from its equilibrium position. Vector p_ω is in phase with I_R and represents the alternating pressure in cavity 3 and it is shown resolved into a component $p_\omega \cos \alpha$ in phase with the displacement vector and a component $p_\omega \sin \alpha$ in quadrature with the displacement vector. This quadrature pressure component acting on the area A of the said plane surface, opposite the cavity, resists motion due to oscillations of the plane.

In an alternative embodiment the stabilising cavity is separated from the supporting disc. The plane surface is supported, a short distance from the stabilising system. Figure 7 shows such a system and gas flows into the cavity 3 through the clearance between the said plane surface and the annular surrounding margin of the cavity. This requires the pressure surrounding the cavity to be greater than the pressure at the outlet of the resistance orifice R. Any oscillation of plane modulates the gas stream flowing into the cavity and the stabilising action is exactly the same as in the arrangement of Figure 5.

A further embodiment of the invention is shown in Figure 8. Here the clearance h, between the pad and the said plane surface of body 1 is enlarged as compared with the previously described embodiments. The effect of this is that the said plane surface is attracted towards the pad when gas under pressure is forced through the entry hole 4 into the clearance space.

This is a well known phenomenon and the explanation of it is apparent on inspection of Figure 2 where it is seen that, with clearances above a certain size (.002 in the instance to which Figure 2 relates), the force F becomes negative.

The attractive force is approximately proportional to the pressure in the gas entry hole 4.

Gas is supplied to the clearance space through a narrow inlet 20 having a resistance R into a cavity 3 of capacity C and thence through hole 4 into the clearance space between the pad and the said plane surface.

The various phase relationships are illustrated vectorially in Figure 9. If the said plane surface oscillates at a frequency f and with an amplitude ϵ the pressure in the cavity 3 will have an alternating component p_ω.

If the flow of gas entering the cavity 3 through resistive passage 20 is constant and supposing that the pressure ratio across is greater than 2, the alternating component of the current I_B, in the entry hole 4 is given by the equation $I_B = p_\omega \omega C$ (where $\omega = 2\pi f$) and is in quadrature with the pressure p_ω. The effective size of entry hole 4 varies inversely with the clearance h and it has a resistance R_o (its resistance with the body 1 stationary and the clearance at its normal or mean value) and when the said plane surface of 1 is oscillating, a varying component of resistance R_ω is added.

The left hand diagram of Figure 9 shows a current vector $I_{R_o} = \frac{p_\omega}{R_o}$ leading the current I_B by 90° and the resultant of these two currents (I_B and I_{R_o}) is I_ϵ and is in antiphase with the displacement vector ϵ, shown dotted on the right hand diagram of the Figure.

The alternating pressure component p_ω is in phase with I_{R_o} and it can be resolved into a component $p_\omega \cos \alpha$ in phase with the displacement vector ϵ, and a component $p_\omega \sin \alpha$ in quadrature with the displacement vector ϵ so that when h is increasing p_ω is large, thus resisting the increase of h.

A further embodiment of the invention is illustrated in Figure 10.

A shallow cavity 3 is formed in the surface of the pad facing the said plane surface of the object 1. Gas supply to the cavity 3 is controlled by a pneumatic amplifier which responds to pressure variations in cavity 3 with a lagging phase relationship.

The response is such that an increase of pressure in cavity 3 results in a decrease of current.

Gas enters a cavity 11 from which a passage 4 leads to cavity 3. A diaphragm 5, which forms one wall of cavity 11, co-operates with a raised seating 6 formed at the end of passage 4 remote from cavity 3, to control the flow of gas into cavity 3. Diaphragm 5 is urged towards seating 6 by a spring 7 which may be adjusted by means of a screwed plug 7*a*. The other side of diaphragm 5 forms a wall of a closed cavity 9 the only access to which is through a hole 10 in diaphragm 5.

Gas at constant pressure is supplied to cavity 11 and lifts diaphragm 5 off the valve seating 6 against the force of spring 7 thus admitting

gas to cavity 3. Gas entering cavity 3 escapes through the clearance between the surface of the wall surrounding cavity 3 and the said plane surface of 1. Gas from cavity 3 also leaks into cavity 9 through a resistance constituted by the hole 10 in diaphragm 5, though an alternative passage could be provided. The pressure in cavity 9 builds up with a time constant $t=R_{10}C_9$ where R_{10} is the resistance of hole 10 and C_9 is the capacity of cavity 9. Equilibrium is reached when the pressure in cavity 9 becomes equal to the pressure in cavity 3. The volume of cavity 3 is made as small as possible.

In the steady state let p_o be the pressure in cavity 3 and R_o the resistance of the leak past the edges of the cavity 3.

If the said plane surface oscillates at a frequency f the pressure in cavity 3 becomes p_o+p_ω and the resistance of the leak becomes R_o+R_ω.

The current leaking past the edges of cavity 3 is given by the expression

$$\frac{P_O+P_\omega}{R_O+R_\omega}$$

For small amplitudes of oscillation this expression may be expanded to

$$\frac{P_O}{R_O}+\frac{P_\omega}{R_O}-\frac{P_O\cdot R_\omega}{R_O^2}-\frac{P_\omega\cdot R_\omega}{R_O^2}$$

The last term is small and may be neglected. The first term represents the steady component of flow through cavity 3.

In cavity 9 the phase of the pressure lags behind the phase of the pressure in cavity 3. The alternating component I_3 of the current entering cavity 3 is in antiphase with this pressure.

Vector diagrams for the pressures and currents are shown in Figure 11.

The second term of the above expanded expression for the current may be called I_{Ro} and is represented by the vertical vector of the left hand part of Figure 11.

Joined to the top of this is the vector I_{10} representing the current through hole 10. Joined to the bottom of the I_{Ro} vector is the vector I_6 representing the current passing through the varying space between the diaphragm 5 and the seating 6. $I_6=g\frac{(I_{10})}{(\omega C_9)}$ and the term in brackets represents the movement of diaphragm 5 whilst the symbol g represents the amplification factor (or gain) of the pneumatic amplifier constituted by the valving action of diaphragm 5 in co-operation with seating 6. Joined to the left hand end of vector I_6 is vector I_3 which is equal to $p_\omega\omega C_3$ and represents the current flowing in cavity 3. Joining the ends of vectors I_3 and I_{10} is the vector $I\epsilon$ which represents the third term of the above expanded expression for current, namely

$$\frac{P_O\cdot R_\omega}{R_O^2}$$

which is in phase with the oscillatory displacement of the said plane surface.

The right hand side of Figure 11 shows the pressure vectors. A vertical vector p_ω is parallel to the I_{Ro} current vector and the displacement vector ϵ, which is shown by a dotted line, is parallel to the $I\epsilon$ vector on the left. The pressure vector p_ω may be resolved in to two vectors, $p_\omega \cos\alpha$ in antiphase with the displacement vector ϵ and $p_\omega \sin\alpha$ in quadrature with the displacement vector ϵ which latter component, acting on the said plane surface, resists oscillation thereof, and by a suitable choice of values, stability may be ensured.

The said plane surface, in the absence of any oscillatory tendency, will take up a position in relation to the pad which depends principally on the amount of gas entering cavity 3, which may be regulated by adjustment of spring 7 by means of spring 7*a*.

In a practical application, for instance to a sliding carriage required to move in one direction along a slideway, five supporting pads could be used, mounted on two inclined planes on a slideway, and co-operating with two correspondingly inclined flat planes on the carriage. Two longitudinally displaced pads would co-operate with each inclined plane and a fifth pad would be required on one of the planes, vertically displaced from the other two pads in that plane, to prevent rotation of the carriage around the axis of intended movement. Not all these pads need necessarily incorporate oscillation stabilising cavity systems and those not so equipped could take the form of Figure 1 or 3. In such a case the oscillation stabilising cavity systems would be confined to the positions required to suppress oscillation in directions where oscillation might be expected to occur.

In such an arrangement the five pads would act in opposition to the weight of the carriage, which would generally be sufficient to avoid lifting of the carriage but downwardly facing pads could also be furnished if required.

In the above description, the pads have been shown as co-operating with a plane surface on the object supported. This surface need not necessarily be flat, of course and could be

part cylindrical or part spherical for instance the upper surfaces of the pad being correspondingly shaped.

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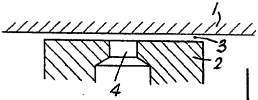


FIG.1.

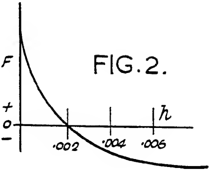


FIG.2.

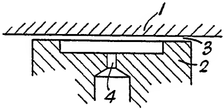


FIG.3.

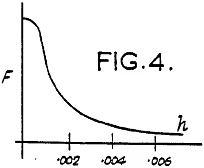


FIG.4.

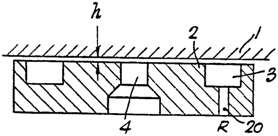


FIG.5.

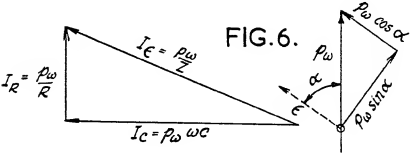


FIG.6.

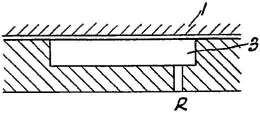


FIG.7.

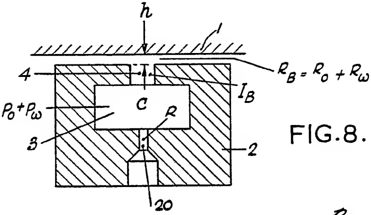


FIG.8.

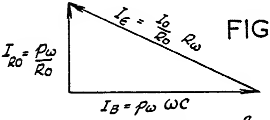
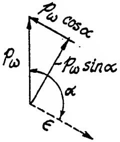


FIG.9.



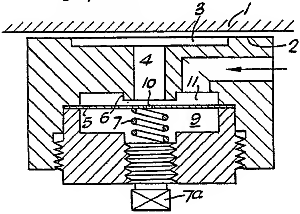
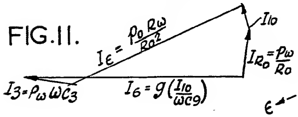
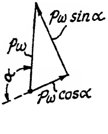
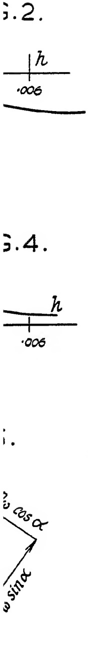


FIG.10.

FIG.11.







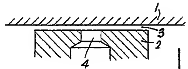


FIG.1.

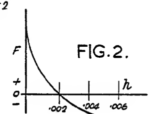
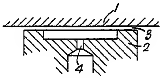


FIG.2.



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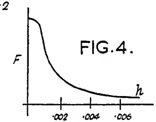

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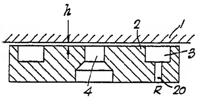

FIG.5.

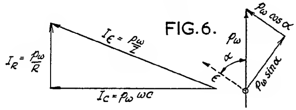

FIG.6.

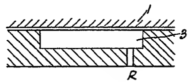

FIG.7.

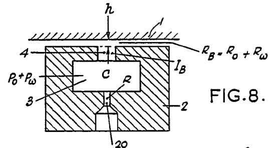

FIG.8.

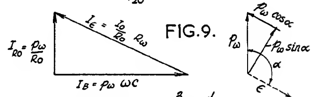

FIG.9.

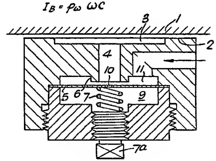

FIG.10.

FIG.11.